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PONDAGE CORRECTIONS INVOLVED IN MEASURING SURFACE RUN-OFF FROM SMALL DRAINAGE BASINS

BY

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Next to developing satisfactory methods for estimating run-off with the present limited store of knowledge the actual measurement of surface run-off involved in securing adequate basic data is the most formidable task of the hydrologist. Among the many kinks in this knotty problem such as silting of measuring devices and instrumental difficulties, the error due to pondage is one of the big ones. The straightening of this one kink is the subject of this paper. The writers hope that this discussion of the pondage correction and its implications will prove helpful to the engineer engaged in the design of impounding reservoirs and to serious students of run-off phenomena.

The extremely flashy run-off and the almost immediate response of surface run-off to intense rainfall make it impossible to secure information on rates of run-off from small drainage basins by ordinary current meter measurements. With the type of precipitation prevailing in some localities the rates of run-off from drainage basins of 3,000 acres or more can, under certain conditions, be determined by means of current meter measurements. In other localities the run-off from drainage basins of the same size and similar characteristics may be too flashy to be measured with a current meter. It is, therefore, difficult to define the term "small drainage basin." However, for the purpose of this paper drainage basins of 2,000 acres or less will, in general, be considered small.

Fig. 1 illustrates a chart from a waterstage recorder on a drainage basin of about 500 acres near Safford, Ariz. This run-off station and the others referred to in this paper are of the type described in Runoff From Small Drainage Basins by D. B. Krimgold, Agricultural Engineering, October 1938. This chart shows a change in stage of 1.71 at 4:44 P.M. to 3.71 at 4:46 P.M., September 3, 1938, which is a rate of rise of 1' per minute. Such rapid rises are not unusual for drainage basins of this size, and are quite common on smaller basins. It is obviously futile to attempt to secure run-off data by means of current meter measurements under such conditions. Precalibrated measuring devices with a stable stage-discharge relationship must therefore be employed to obtain satisfactory records of rates of run-off as well as of total yields from such drainage basins.

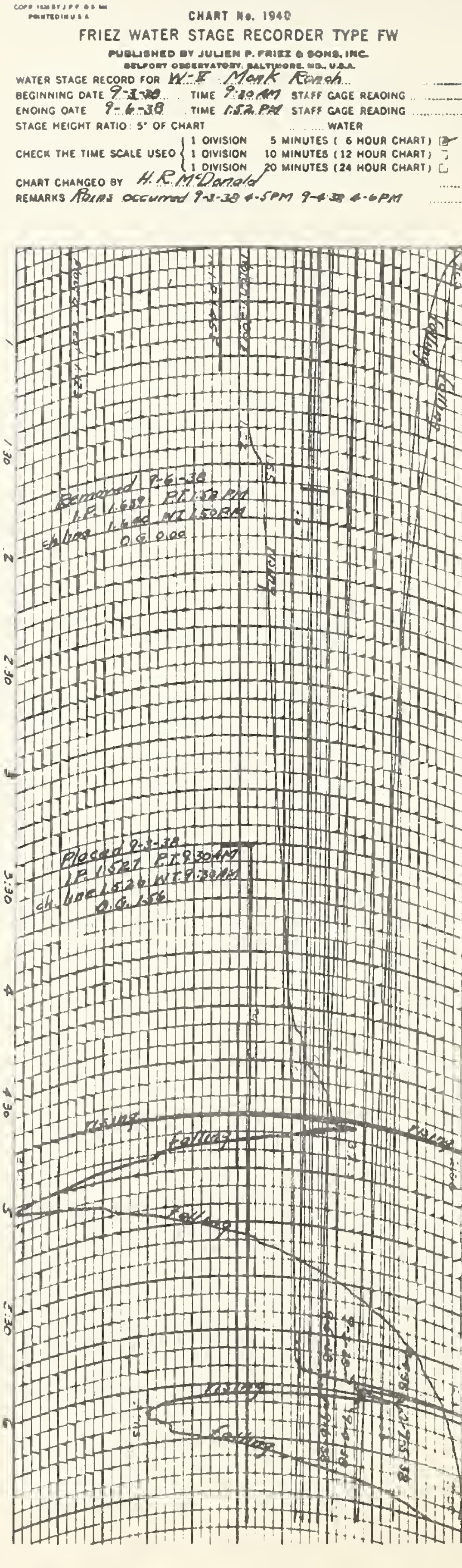

FIGURE 1. WATER STAGE RECORDER CHART FROM A DRAINAGE BASIN OF ABOUT 500 ACRES NEAR SAFFORD, ARIZONA, SHOWING A HIGH RATE OF CHANGE IN STAGE

So far no practical device has been developed which will measure run-off accurately without constricting the channel and creating a certain amount of artificial pondage. Several types of weirs and flumes are available for measuring run-off. The degree of contraction required for the proper operation of the several available devices varies with the type of structure. Broad-crested V-notch weirs require little contraction and can be fitted to the natural or artificial watercourse by choosing the proper side slopes which will give the required degree of accuracy, but even these structures create pondage which must be considered in arriving at the true rates of surface run-off.

Fig. 2 shows the surface of pondage for a fairly high stage at a run-off station on the Freehold, N. J., project of the Soil Conservation Service. This run-off station is a broad-crested V-notch weir with 2:1 side slopes constructed in a channel with about the same side slopes. Although the pondage at this station is small it, nevertheless, has to be considered in arriving at the correct rates of surface run-off during high rates of change in stage, such as illustrated in fig. 1. It is practically always necessary to consider pondage because while the volumes of water involved may in some cases be small, the rates of change in stage may be great enough to make the rate of impounding of water on rising stages or the rate at which the water drains out of the pond on falling stages a large percentage of the value given by the rate of discharge of the weir or flume.

A method described herein for the quantitative determination of rates of run-off represented by pondage was developed by the writers. Pondage corrections obtained by this method were applied to a considerable number of records of surface run-off from small drainage basins equipped with broad-crested V-notch weirs. The results were rather interesting and revealed that in cases of rapid rises in stage the pondage corrections may amount to as much as 50% or more of the apparent peaks obtained from the rating tables of the weirs, that the corrected maximum peaks of surface run-off occur prior to the times of the maximum gage heights, that the pondage corrections enable the determination of the actual time of ending of surface run-off, and that they also bring out minor peaks of run-off resulting from high rainfall intensities of short duration which do not appear if the pondage correction is neglected.

To illustrate the manner in which the pondage corrections affect records of run-off, the rainfall and resulting run-off of April 4 and 5, 1939 on a 130-acre drainage basin on the Vega, Texas, project of the Soil Conservation Service were computed and both corrected and uncorrected hydrographs were plotted. The run-off station on this drainage basin is shown in fig. 3. This photograph was taken in April 1938 and shows two intake pipes. The pipes were removed before April 1939 and replaced by an intake channel and a series of slots in the stilling well to permit an uninterrupted and direct connection between the stilling well and the channel of approach.

FIGURE 2. SURFACE OF PONDAGE FOR A FAIRLY HIGH STAGE AT A BROAD-CRESTED V-NOTCH WEIR WITH 2 : 1 SIDE SLOPES NEAR FREEHOLD, NEW JERSEY

FIGURE 3. RUNOFF STATION ON A DRAINAGE BASIN OF 130 ACRES NEAR VEGA, TEXAS

A topographic map of the pondage at this station is shown in fig. 4. For the lack of better expressions the contours at notch elevation and at maximum stage for which the weir was designed were designated "permanent" and "temporary pondage" respectively on this map.

In fig. 5 are given the mass curve of rainfall, a histogram of rainfall intensities, the run-off hydrograph based on uncorrected rates of run-off, the corrected run-off hydrograph, the mass curve of run-off based on the corrected hydrograph, and the graphical determination of the actual time of ending of run-off. This figure also contains a table entitled "Record of Rainfall and Run-off" for the April 4 - 5 storm referred to above. The data given in columns 1, 3, 6, and 8 of this table were taken from the charts of the recording rain gage on this watershed and of the water level recorder at the run-off station. The values given in the other columns were computed.

A close examination of fig. 5 will reveal the following points: The pondage correction does not change the time of beginning of run-off. It does, however, show that the actual maximum peak occurred 2 minutes prior to maximum gage height and was 34.5% greater than the peak shown by the uncorrected hydrograph at the maximum gage height. The corrected hydrograph shows two secondary sharp peaks at 8:54 P.M. and 9:03 P.M. which are in closer agreement with the histogram of rainfall intensities than the one secondary peak at 9:04 P.M. of the uncorrected hydrograph. The corrected hydrograph also shows that the actual duration of surface run-off was 2 hr. 9 min. instead of 3 hr. 52 min. as indicated by the uncorrected hydrograph. The portion of the uncorrected hydrograph between 11:02 P.M. April 4 and 12:45 A.M. April 5 does not represent surface run-off. In this particular case it represents the rate at which the impounded water drains out of the pond. In other cases, the portion of the uncorrected hydrograph beyond the time of ending of surface run-off may represent both the rate at which the pond is draining and ground water flow.

The principles underlying the concept of the pondage correction can be demonstrated most adequately by a discussion of the manner in which the corrections for the station illustrated in figs. 3 and 4 were developed and applied to the record given in fig. 5.

The pondage correction to be applied to the discharge at a given stage is the <u>rate</u> of ponding and not the <u>total volume</u> impounded at that stage. To determine this rate of ponding at any given stage in case of small ponds such as would exist on small drainage basins one must know the rate of change in stage during an interval of time <u>just prior</u> to the instant at which this stage was reached $\left(\frac{dh}{dt}\right)$, and

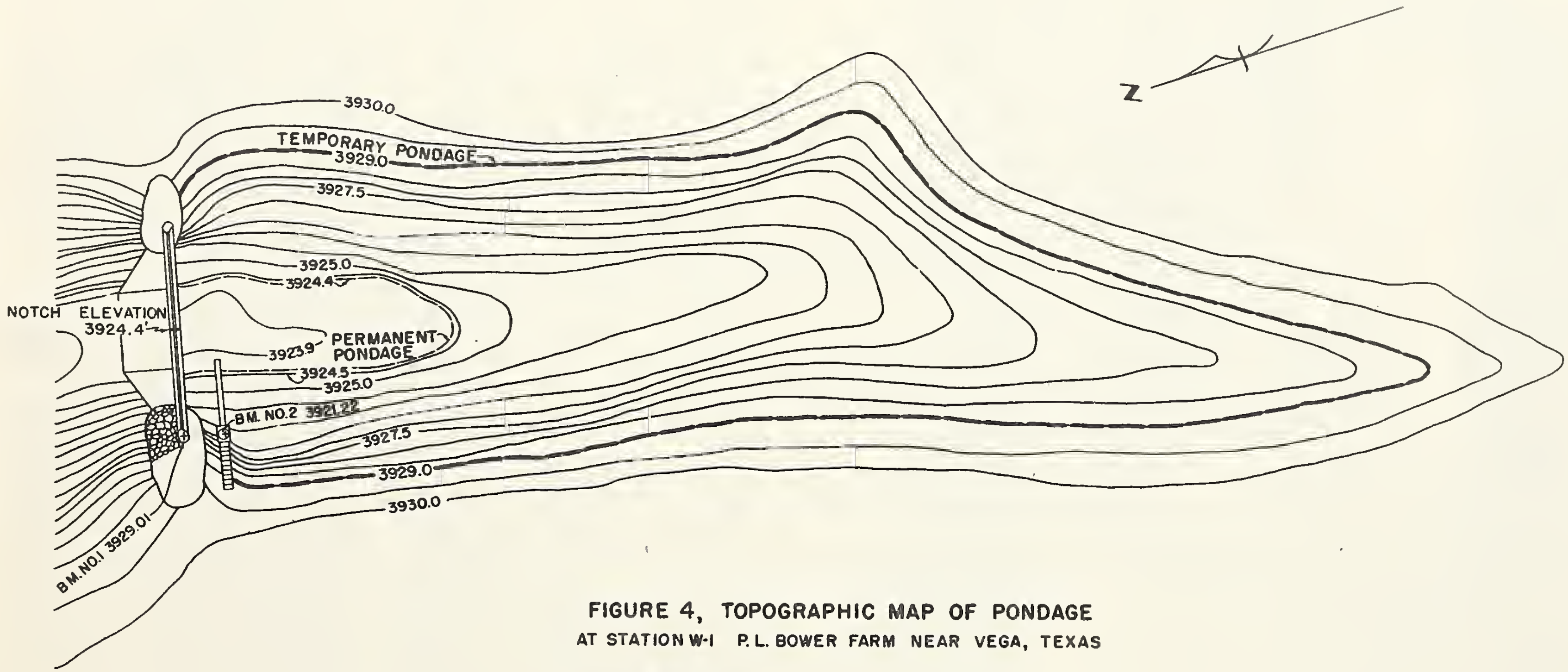

FIGURE 4, TOPOGRAPHIC MAP OF PONDAGE
AT STATION W-1 P. L. BOWER FARM NEAR VEGA, TEXAS

0 20 40
SCALE IN FEET

CONTOUR INTERVAL 0.5'

GAGE DATUM ELEVATION OF NOTCH = 1.500 FEET

Record of Rainfall and Runoff

for April 4, 1939 from Stations R-1 and W-I (P.L.Bower) near Vega Texas

Drainage Area 129.37 Acres   Conversion Factor : 1 Second-foot = 0.00766598 Inches per Hour

Rainfall					Runoff									
Date and Time	Time Interval	Accumulated Depth	Depth for Time Interval	Intensity	Date and Time	Time Interval	Gage Height •	Rate of Change in Stage	Pondage Correction Q_p	Weir Discharge Q_w	Discharge Corrected for Pondage $Q_w \pm Q_p$	Accumulated Runoff Based on $Q_w \pm Q_p$	Accumulated Runoff Based on Q_w	Remarks
	Minutes	Inches	Inches	In/Hr		Minutes	Feet	Ft/Min	Sec.ft.	Sec.ft	Sec.ft	Inches	Inches	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Apr. 4 8:45P	0	0			Apr. 4 8:45P		•1.50							Rain Began
8:48	3	0.21	0.21	4.20										
8:52	4	0.41	0.20	3.00	8:52		1.50	0	0	0				
					8:53	0	1.50	0	0	0	0	0	0	Runoff Began
					8:54	1	1.65	0.15	3.30	0.101	3.40	0.0002	0.0000	Peak
8:57	5	0.51	0.10	1.20	8:57	3	1.74	0.03	0.705	0.338	1.04	0.0010	0.0001	Trough
					9:00P	3	1.84	0.0333	0.832	0.840	1.67	0.0015	0.0003	
9:02P	5	0.70	0.19	2.28	9:02	2	1.90	0.03	0.801	1.20	2.00	0.0020	0.0006	
					9:03	1	1.98	0.08	2.30	2.00	4.30	0.0024	0.0008	Peak
					9:04	1	1.99	0	0	2.10	2.10	0.0028	0.0011	
					9:05	1	1.99	0	0	2.10	2.10	0.0031	0.0014	
9:07	5	0.74	0.04	0.48										
					9:08	3	1.96	-0.01	-0.288	1.80	1.51	0.0038	0.0022	Trough
					9:09	1	1.94	0	0	1.60	1.60	0.0040	0.0024	
					9:10	1	2.36	0.42	19.8	9.15	29.0	0.0060	0.0031	
					9:11	1	2.64	0.28	15.7	19.0	34.7	0.0101	0.0049	Maximum Peak
					9:12	1	2.76	0.12	7.74	24.8	32.5	0.0144	0.0077	
					9:13	1	2.78	0	0	25.8	25.8	0.0181	0.0109	
					9:14	1	2.76	-0.02	-1.29	24.8	23.5	0.0213	0.0141	
9:15	8	0.76	0.02	0.15	9:15	1	2.74	-0.02	-1.21	23.8	22.6	0.0242	0.0172	Rain Ceased
					9:17	2	2.70	-0.02	-1.21	21.8	20.6	0.0297	0.0230	
					9:20	3	2.60	-0.0333	-1.88	17.4	15.5	0.0366	0.0305	
					9:23	3	2.50	-0.0333	-1.73	13.4	11.7	0.0418	0.0364	
9:25	10	0.76	0	0										Rain Resumed
					9:26	3	2.40	-0.0333	-1.58	10.4	8.82	0.0457	0.0410	
					9:30	4	2.30	-0.025	-1.06	7.60	6.54	0.0496	0.0456	
9:34	9	0.78	0.02	0.13										Rain Ended
					9:35	5	2.20	-0.02	-0.740	5.35	4.61	0.0532	0.0497	
					9:41	6	2.10	-0.0167	-0.529	3.55	3.02	0.0561	0.0531	
					9:48	7	2.00	-0.0143	-0.412	2.20	1.79	0.0582	0.0557	
					9:58	10	1.90	-0.01	-0.267	1.20	0.933	0.0599	0.0579	
					10:10P	12	1.80	-0.0083	-0.208	0.600	0.392	0.0609	0.0593	
					10:32	22	1.70	-0.0045	-0.106	0.213	0.107	0.0616	0.0604	
					11:08	36	1.60	-0.0028	-0.061	0.037	-0.024		0.0610	Runoff Ended at 11:02 P (By plotting plus and minus values at 10:32 P and 11:08 P)
					Apr. 5 12:45A	97	1.50	-0.0010	-0.020	0			0.0613	
					Apr. 4 10.32P	22	1.70	-0.0045	-0.106	0.213	0.107	0.0616		Computation of Accumulated Runoff at End of Surface Runoff
					11:02	30	1.62	-0.0027	-0.059	0.059	0	0.0618		

• 1.50 is the Gage Height of Zero Flow

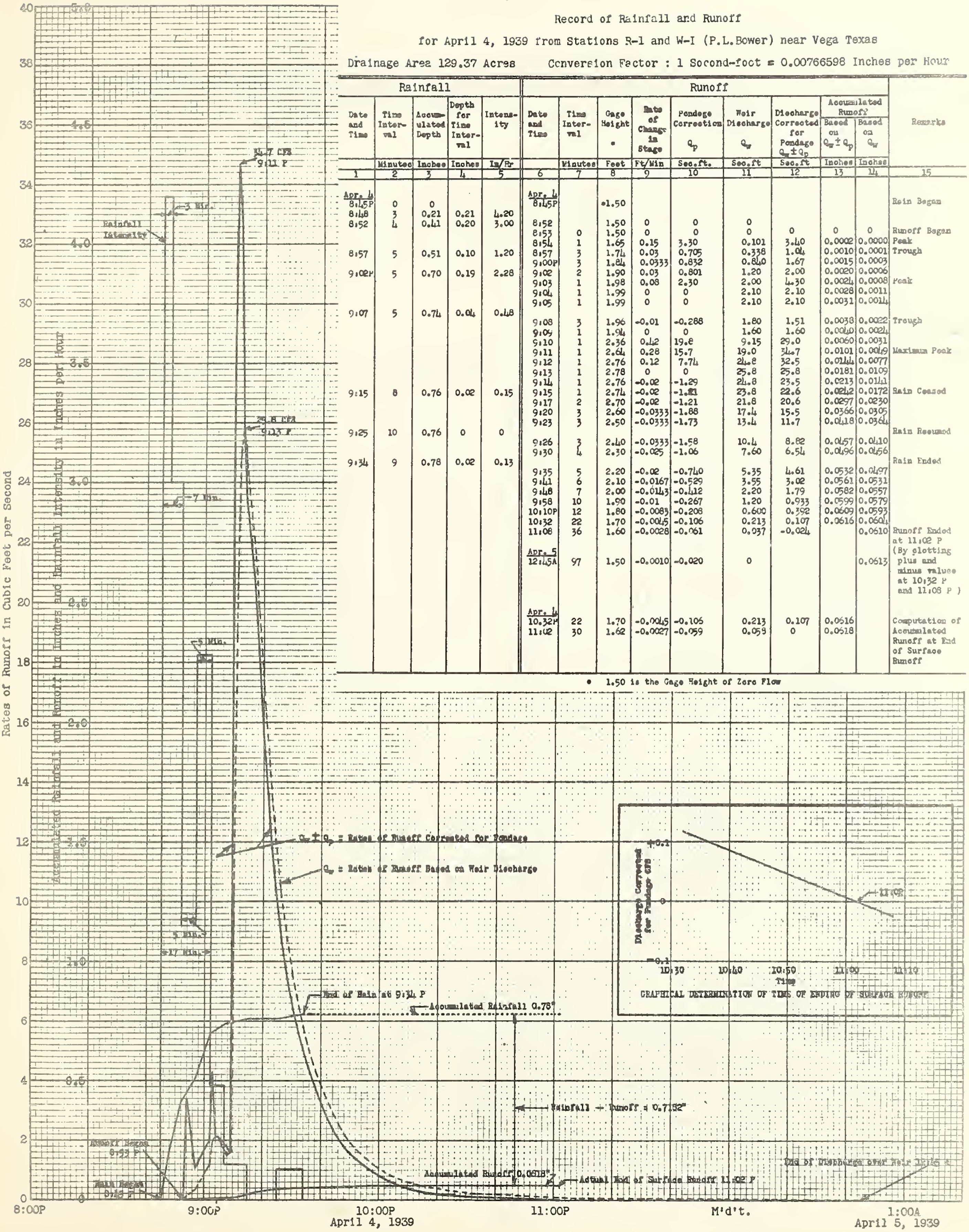

FIGURE 5. HYDROGRAPH AND RECORD OF RAINFALL AND RUNOFF SHOWING EFFECT OF PONDAGE CORRECTION AT STATION W-I (P.L.BOWER) NEAR VEGA, TEXAS

the differential volume corresponding to that stage $\frac{(dv)}{(dH)}$. This implies an assumption that the level of the <u>entire</u> ponded area changes simultaneously with the elevation of the water surface at the point at which the stage is measured.

Due to the limitations of the waterlevel recorders used on the run-off measuring stations the time and stage cannot be determined closer than the nearest minute and the nearest 0.01' respectively. For this and other reasons discussed below the values of 0.01' per minute and 0.01' of stage for the rate of change in stage $\frac{(dh)}{(dt)}$ and for the differential volume $\frac{(dv)}{(dH)}$ respectively were used in developing the basic values of the pondage corrections. With the principles and limitations outlined above in mind the pondage corrections for the station illustrated in figs. 3 and 4 were developed in the following manner. The area in square feet included within each of the 0.5' contours and the contours of permanent and temporary pondage shown in fig. 4 were determined by means of a planimeter. The volume corresponding to a depth of 0.01' at each of the contours was determined by multiplying each of the areas by 0.01. The corresponding rates of ponding in cubic feet per second for a rate of change in stage of 0.01' per minute were obtained by dividing each of the volumes by 60. The values of areas, volumes, and rates of ponding were tabulated in columns 2, 3, and 5 of the table shown in fig. 6. Columns 1 and 4 of this table give mean sea level and corresponding stage gage datum elevations of the contours as well as of intermediate elevations discussed below. Stage gage datum elevations are the elevations of the water surface upstream from the weir referred to the elevation of the notch which for various reasons entering into the setting of the recorder was in this case taken to be 1.500'.

The several rates of ponding thus obtained were plotted against the corresponding stage gage datum elevation which resulted in the pondage correction curve shown in fig. 6. Rates of ponding at each 0.1' of stage were determined from this curve and the values incorporated in the table. It was not considered necessary to tabulate values for lesser intervals of stage since they could, if necessary, be determined with sufficient accuracy by simple interpolation.

The pondage corrections were then incorporated in what is called the final rating table for this station which is illustrated in fig. 7. This table gives values of weir discharge (Q_W) for each 0.01' of stage in cubic feet per second and values of the pondage corrections (Q_p) in cubic feet per second for rates of change in stage from 0.01' per minute to 0.09' per minute for each 0.1' of stage. It should be noted that the values of Q_p begin with a stage of 1.10 while the values of Q_W begin with 1.50 which is the gage height (stage) of zero flow over the weir. The values of Q_p for stages less than 1.50 are used to obtain records of initial rates of run-off for stages below the elevation of the notch.

Contour Elevation ft. (1)	Area sq.ft. (2)	Volume for 0.01' of stage cu.ft. (3)	Stage G.D.E. ft. (4)	Rate of Ponding for 0.01'/minute change in stage c.f.s. (5)
3923.6	0	0	0.7	0
			0.8	.014
			0.9	.030
3923.9	286	2.86	1.0	.048
			1.1	.078
			1.2	.110
			1.3	.142
			1.4	.173
3924.4	1193	11.98	1.5	.200
3924.5	1320	13.20	1.6	.220
			1.7	.235
			1.8	.250
			1.9	.267
			2.0	.288
3925.0	1900	19.00	2.1	.317
			2.2	.370
			2.3	.422
			2.4	.472
			2.5	.520
3925.5	3380	33.80	2.6	.563
			2.7	.603
			2.8	.645
			2.9	.689
			3.0	.732
3926.0	4644	46.44	3.1	.774
			3.2	.820
			3.3	.865
			3.4	.910
			3.5	.955
3926.5	6018	60.18	3.6	1.00
			3.7	1.04
			3.8	1.09
			3.9	1.14
			4.0	1.19
3927.0	7464	74.64	4.1	1.24
			4.2	1.29
			4.3	1.35
			4.4	1.41
			4.5	1.47
3927.5	9094	90.94	4.6	1.52
			4.7	1.58
			4.8	1.63
			4.9	1.69
			5.0	1.75
3928.0	10840	108.40	5.1	1.81
			5.2	1.88
			5.3	1.96
			5.4	2.04
			5.5	2.12
3928.5	13134	131.34	5.6	2.19
			5.7	2.26
			5.8	2.33
			5.9	2.40
			6.0	2.48
3929.0	15376	153.76	6.1	2.56

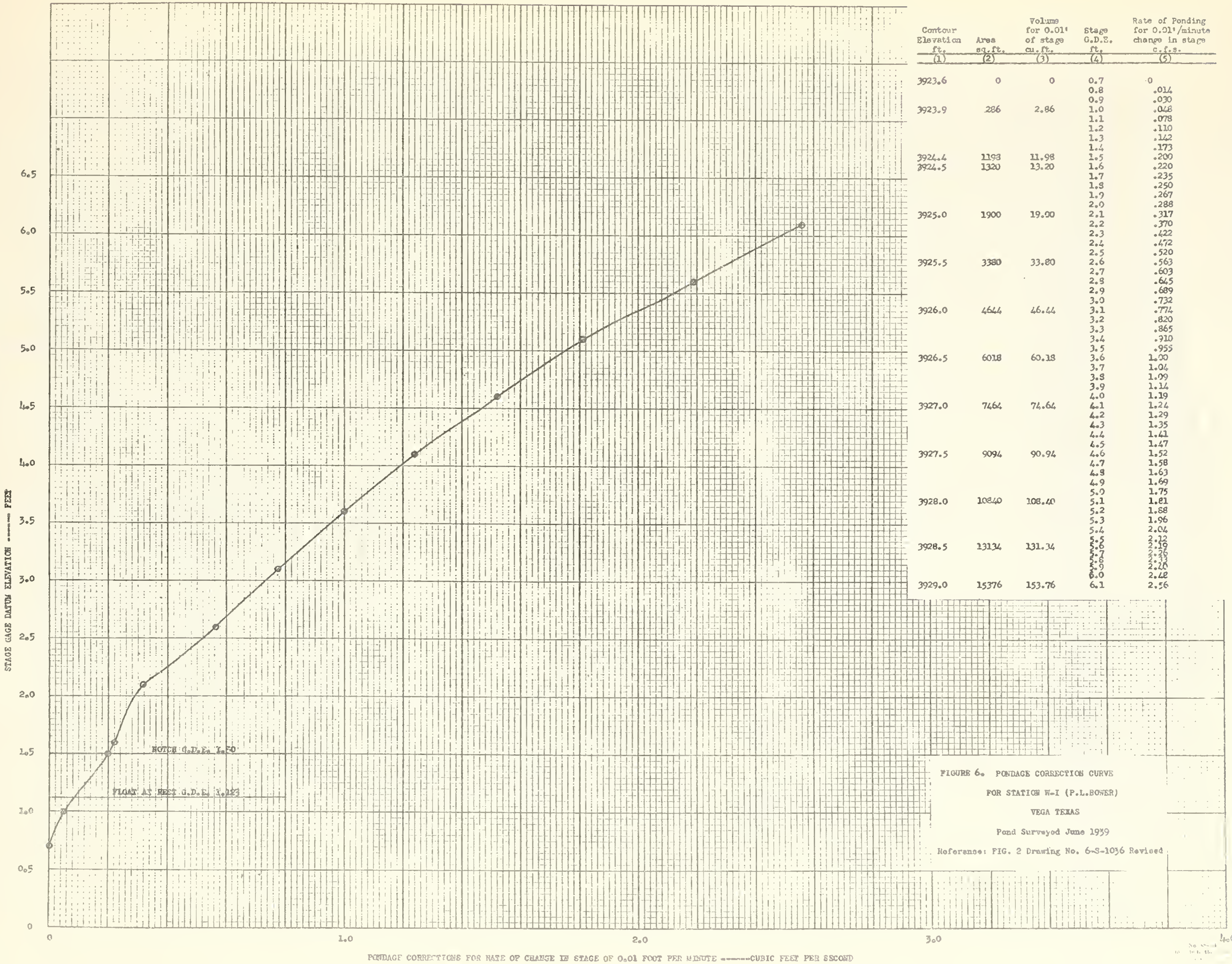

FIGURE 6. PONDAGE CORRECTION CURVE

FOR STATION W-I (P.L.BOWER)

VEGA TEXAS

Pond Surveyed June 1939

Reference: FIG. 2 Drawing No. 6-S-1036 Revised

RATING TABLE FOR STATION W-I (P.L.BOWER) VEGA, TEXAS

APPLIES TO FOLLOWING PERIOD: MARCH '38 TO OCT. '39 TO

G.D.E. = GAGE DATUM ELEVATION

G.D.E. OF ZERO FLOW OVER WEIR = 1.50

REFERENCE: DRAWING NO. 6-S-1036 REVISED.

G.D.E. OF ORIGINAL POINT OF ZERO PONDAGE = 0.70

G.D.E. OF "FLOAT AT REST" (LOWEST POSITION OF FLOAT) = 1.123

CROSS-SECTIONS TAKEN AND POND SURVEYED JUNE 1939.

Q_w - Weir Discharge for each 0.01' of stage - Cubic Feet per Second (Upper Line)
Q_p - Pondage Corrections for Rates of Change in Stage of 0.01' per minute to 0.09' per minute - Cubic Feet per Second (Lower Line)

Stage G.D.E.	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
1.10	– –	– .078	– .156	– .234	– .312	– .390	– .468	.546	– .624	– .702
1.20	– –	– .110	– .220	– .330	– .440	– .550	.660	.770	.880	.990
1.30	– –	– .142	– .284	– .426	– .568	– .710	.852	.994	1.14	1.28
1.40	– –	– .173	– .346	– .519	.692	– .865	– 1.04	1.21	1.38	– 1.56
1.50	– –	– .200	.001 .400	.002 .600	.004 .800	.006 1.00	.010 1.20	.015 1.40	.021 1.60	.028 1.80
1.60	.037 –	.047 .220	.058 .440	.071 .660	.065 .880	.101 1.10	.120 1.32	.140 1.54	.162 1.76	.187 1.98
1.70	.213 –	.241 .235	.272 .470	.303 .705	.338 .940	.373 1.18	.414 1.41	.455 1.64	.500 1.88	.545 2.12
1.80	.600 –	.660 .250	.720 .500	.780 .750	.840 1.00	.900 1.25	.960 1.50	1.02 1.75	1.08 2.00	1.14 2.25
1.90	1.20 –	1.30 .267	1.40 .534	1.50 .801	1.60 1.07	1.70 1.34	1.80 1.60	1.90 1.87	2.00 2.14	2.10 2.40
2.00	2.20 –	2.30 .288	2.40 .576	2.50 .864	2.65 1.15	2.80 1.44	2.95 1.73	3.10 2.02	3.25 2.30	3.40 2.59
2.10	3.55 –	3.70 .317	3.85 .634	4.00 .951	4.15 1.27	4.35 1.58	4.55 1.90	4.75 2.22	4.95 2.54	5.15 2.85
2.20	5.35 –	5.55 .370	5.75 .740	5.95 1.11	6.15 1.48	6.35 1.85	6.60 2.22	6.85 2.59	7.10 2.96	7.35 3.33
2.30	7.60 –	7.85 .422	8.10 .844	8.35 1.27	8.60 1.69	8.85 2.11	9.15 2.53	9.45 2.95	9.75 3.38	10.1 3.80
2.40	10.4 –	10.7 .472	11.0 .944	11.3 1.42	11.6 1.89	11.9 2.36	12.2 2.83	12.5 3.30	12.8 3.78	13.1 4.25
2.50	13.4 –	13.8 .520	14.2 1.04	14.6 1.56	15.0 2.08	15.4 2.60	15.8 3.12	16.2 3.64	16.6 4.16	17.0 4.68
2.60	17.4 –	17.8 .563	18.2 1.12	18.6 1.69	19.0 2.25	19.4 2.82	19.8 3.38	20.3 3.94	20.8 4.50	21.3 5.07
2.70	21.8 –	22.3 .603	22.8 1.21	23.3 1.81	23.8 2.41	24.3 3.02	24.8 3.62	25.3 4.22	25.8 4.82	26.3 5.43
2.80	26.8 –	27.3 .645	27.8 1.29	28.4 1.94	29.0 2.58	29.6 3.22	30.2 3.87	30.8 4.52	31.4 5.16	32.0 5.80
2.90	32.6 –	33.2 .689	33.8 1.38	34.4 2.07	35.0 2.76	35.6 3.44	36.2 4.13	36.9 4.82	37.6 5.51	38.3 6.20
3.00	39.0 –	39.7 .732	40.4 1.46	41.1 2.20	41.8 2.93	42.5 3.66	43.2 4.39	43.9 5.12	44.6 5.86	45.3 6.59
3.10	46.0 –	46.8 .774	47.6 1.55	48.4 2.32	49.2 3.10	50.0 3.87	50.8 4.64	51.6 5.42	52.4 6.19	53.2 6.97
3.20	54.0 –	54.8 .820	55.6 1.64	56.5 2.46	57.4 3.28	58.3 4.10	59.2 4.92	60.1 5.74	61.0 6.56	61.9 7.38
3.30	62.8 –	63.7 .865	64.6 1.73	65.5 2.60	66.5 3.46	67.5 4.32	68.5 5.19	69.5 6.06	70.5 6.92	71.5 7.78
3.40	72.5 –	73.5 .910	74.5 1.82	75.5 2.73	76.5 3.64	77.5 4.55	78.5 5.46	79.5 6.37	80.5 7.28	81.6 8.19
3.50	82.7 –	83.8 .955	84.9 1.91	86.0 2.86	87.1 3.82	88.2 4.78	89.3 5.73	90.4 6.68	91.5 7.64	92.6 8.60
3.60	93.8 –	95.0 1.00	96.2 2.00	97.4 3.00	98.6 4.00	99.8 5.00	101 6.00	102 7.00	103 8.00	105 9.00
3.70	106 –	107 1.04	108 2.08	110 3.12	111 4.16	113 5.20	114 6.24	115 7.28	116 8.32	117 9.36
3.80	119 –	120 1.09	121 2.18	123 3.27	124 4.36	126 5.45	127 6.54	128 7.63	130 8.72	131 9.81
3.90	133 –	134 1.14	135 2.28	137 3.42	139 4.56	140 5.70	142 6.84	143 7.98	145 9.12	146 10.3

Stage G.D.E.	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
4.00	148 –	149 1.19	151 2.38	152 3.57	154 4.76	155 5.95	157 7.14	159 8.33	160 9.52	162 10.7
4.10	163 –	165 1.24	167 2.48	168 3.72	170 4.96	172 6.20	174 7.44	175 8.68	177 9.92	179 11.2
4.20	181 –	183 1.29	184 2.58	186 3.87	188 5.16	190 6.45	192 7.74	193 9.03	195 10.3	197 11.6
4.30	199 –	201 1.35	203 2.70	205 4.05	206 5.40	208 6.75	210 8.10	212 9.45	214 10.8	216 12.2
4.40	218 –	220 1.41	222 2.82	224 4.23	226 5.64	228 7.05	230 8.46	232 9.87	234 11.3	236 12.7
4.50	238 –	240 1.47	243 2.94	245 4.41	247 5.88	249 7.35	251 8.82	253 10.3	256 11.8	258 13.2
4.60	260 –	262 1.52	264 3.04	267 4.56	269 6.08	271 7.60	273 9.12	276 10.6	278 12.2	280 13.7
4.70	283 –	285 1.58	287 3.16	289 4.74	291 6.32	294 7.90	296 9.48	299 11.1	301 12.6	303 14.2
4.80	306 –	308 1.63	311 3.26	313 4.89	316 6.52	318 8.15	321 9.78	323 11.4	326 13.0	328 14.7
4.90	331 –	333 1.69	336 3.38	338 5.07	341 6.76	343 8.45	346 10.1	349 11.8	351 13.5	354 15.2
5.00	357 –	359 1.75	362 3.50	365 5.25	367 7.00	370 8.75	373 10.5	376 12.2	379 14.0	382 15.8
5.10	384 –	387 1.81	390 3.62	393 5.43	396 7.24	398 9.05	401 10.9	404 12.7	407 14.5	410 16.3
5.20	412 –	415 1.88	418 3.76	421 5.64	424 7.52	427 9.40	430 11.3	433 13.2	436 15.0	439 16.9
5.30	442 –	445 1.96	448 3.92	451 5.88	454 7.84	457 9.80	460 11.8	463 13.7	467 15.7	470 17.6
5.40	473 –	476 2.04	479 4.08	482 6.12	486 8.16	489 10.2	492 12.2	495 14.3	498 16.3	502 18.4
5.50	505 –	508 2.12	511 4.24	515 6.36	518 8.48	522 10.6	525 12.7	529 14.8	532 17.0	535 19.1
5.60	539 –	542 2.19	546 4.38	549 6.57	553 8.76	556 11.0	560 13.1	563 15.3	567 17.5	570 19.7
5.70	574 –	577 2.26	581 4.52	584 6.78	588 9.04	592 11.3	596 13.6	599 15.8	603 18.1	607 20.3
5.80	611 –	614 2.33	618 4.66	622 6.99	626 9.32	630 11.6	633 14.0	637 16.3	641 18.6	645 21.0
5.90	649 –	652 2.40	656 4.80	660 7.20	664 9.60	668 12.0	671 14.4	675 16.8	679 19.2	683 21.6
6.00	687 –	691 2.48	695 4.96	699 7.44	703 9.92	706 12.4	710 14.9	714 17.4	718 19.8	722 22.3
6.10	726 –	2.56	5.12	7.68	10.2	12.8	15.4	17.9	20.5	23.0

FIGURE 7. RATING TABLE FOR STATION W-I (P.L.BOWER) NEAR VEGA, TEXAS

Some of the items in the heading of this rating table require a word of explanation. The first line indicates that the rating table applies to the period from March 1938 to date. The other date is included to show that the station was checked in October 1939. If, for instance, on March 15, 1940 conditions at the station had changed sufficiently to require a revision of the rating table this line would be completed by adding the words March 15, 1940 to indicate that this rating table applies only to records obtained up to March 15, 1940.

The term "G.D.E., gage datum elevation," has already been explained above. "The original point of zero pondage" is the elevation of the lowest point in the channel above the weir when the station was first put in operation. The point of zero pondage is subject to change due to silting. A record of this change is obtained by periodic surveys which can be referred to in connection with run-off periods occurring when the elevation of water surface is below the float at rest elevation. The float at rest is the lowest position of the float which is definitely fixed by a float rest ring. This elevation is 1.123 and it is for this reason that the values of Q_p in the rating table begin at stage 1.10.

The use of this rating table and the application of the pondage correction can be demonstrated by a few illustrative examples.

Let us first see how the corrected rate of run-off at 9:10 P.M. on the hydrograph shown in fig. 5 was determined. From column 8 of the table Record of Rainfall and Run-off we find that the stage at 9:10 P.M. was 2.36'. The value of Q_w (discharge over the weir) as given in the rating table (fig. 7) is 9.15 c.f.s. The gage height (stage) at 9:09 P.M. was 1.94'. This means that the stage was rising at a rate of 0.42' per minute, just before the stage of 2.36' was reached. Again consulting the rating table (fig. 7) we find that the pondage correction (Q_p) is $(1.69 \times 10) + 0.844 = 17.7$ c.f.s. for a stage of 2.30' and $(1.89 \times 10) + 0.944 = 19.8$ c.f.s for a stage of 2.40'. The correct value for a stage of 2.36' would, therefore, be 19.0 c.f.s It will be noted, however, that rather than interpolate, the value of 19.8 c.f.s was used in the tabulation. This was done because the difference of 0.8 c.f.s would be less than 3% of the corrected rate of 29.0 c.f.s which is beyond the accuracy with which the pondage correction can be determined. The same practice was followed in determining all other values of the pondage correction, that is, the tabular values for the nearest 0.1' of stage were used. Since the stage was rising the pondage correction must be added to the discharge of the weir because the correction represents the rate at which water was impounding just before the stage of 2.36' was reached. The actual rate of surface run-off was, therefore, $9.15 + 19.8 = 29.0$ c.f.s. It is significant that with a rate of rise of only 0.42' per minute the value of Q_p is more than twice the value of Q_w. One needs only refer back to fig. 1 which shows a rate of rise of one foot per minute to realize the magnitude of the error involved in neglecting the pondage correction.

We shall now demonstrate how the pondage correction is applied on falling stages and how the actual time of ending of run-off is determined. Let us consider the rates of run-off at 10:10 P.M. and at 10:32 P.M. in the above-mentioned hydrograph. The gage heights at 10:10 and at 10:32 were 1.80' and 1.70' respectively. This is a drop of 0.1' in 22 minutes or a rate of change (rate of fall in this case) in stage of 0.0045' per minute which means that the water surface in the pond was lowering at this rate <u>just before</u> the stage of 1.70' was reached. For a stage of 1.70' the rating table gives a value of Q_W equal to 0.213 c.f.s. and a value of:

$$Q_p = \left(\frac{0.940}{10} + \frac{1.18}{100}\right) = 0.106 \text{ c.f.s.}$$

The corrected rate of run-off is, therefore, equal to 0.213 - 0.106 = 0.107 c.f.s. The pondage correction is subtracted from the weir discharge because in this case it is the rate at which the water impounded by the weir is draining at this stage. In a similar manner the values of Q_W and Q_p at 11:08 P.M. were found to be 0.037 c.f.s and - 0.061 c.f.s. respectively which resulted in a value of Q = 0.037 - 0.061 = -0.024 c.f.s. This negative value indicates that surface run-off ended between 10:32 P.M. and 11:08 P.M. The actual time of ending of run-off was determined graphically as shown in the lower right corner of fig. 5 and found to be 11:02 P.M.

In discussing the final rating table, mention was made of the original point of zero pondage and of the fixed elevation of float at rest which are below the notch. It so happened that the run-off period under discussion began when the water surface in the channel of approach was at the elevation of the notch (1.50'). Quite often this may not be the case and the rates of run-off for stages below 1.50' must be determined to obtain a complete hydrograph and the correct total volume of run-off. To illustrate how the pondage correction is used to determine such rates, let us assume that the stage was 1.23' at 8:53 P.M. when run-off began. Let us further assume that at 8:54 P.M. the stage as 1.34'. This represents a rate of change in stage of 0.11' per minute and, therefore, a value of Q_p = 1.56 c.f.s. Since at this stage there is no flow over the weir Q_W = 0 and the resulting corrected rate of run-off = Q = $Q_W + Q_p$ = 0 + 1.56 = 1.56 c.f.s. One or more additional rates of runoff, depending on whether or not the rate of rise changed, would be determined in a similar manner for stages below 1.50' which when plotted would define the hydrograph below notch elevation.

It is obvious that at peaks and troughs on the hydrograph the rates of change in stage are zero, that is, at the instants of peaks and troughs the inflow at the station is equal to the outflow. The pondage correction is, therefore, zero.

It should be noted from fig. 5 that while the rates and time of ending of surface run-off differ in the corrected and uncorrected hydrographs, the total volume of run-off based on either hydrograph is the same. This is as it should be in this case if the storage equation (outflow = inflow) is to be satisfied. The slight discrepancy

of 0.8% shown by the last entries in columns 13 and 14 in fig. 5 is well within the accuracy with which the pondage correction can be determined for natural channels. If surface run-off had begun at stage 1.23', that is, below the notch, the total volume based on the uncorrected hydrograph would have been in error. It would have been less than the volume based on the corrected hydrograph by an amount equal to the volume of the pond between elevations 1.23' and 1.50'. The fact that the total volumes given in the last entries of columns 13 and 14 of fig. 5 check as close as they do proves the validity of the pondage correction.

We have already inferred thatthe pondage cannot be determined with a high degree of accuracy. In the case of a natural channel of approach the accuracy is affected by:

(a) Errors in the topographic survey of the so-called "temporary pondage."
(b) Errors in plotting the topographic map.
(c) Errors in planimetering the areas within each of the contours.
(d) Errors in the determination of the rates of change in stage.

Because these errors may be either cumulative or compensating it is impossible to estimate the degree of accuracy of the pondage correction. Let us, however, assume that the total error involved is as high as 20% and see what effect such an error would have on the final rates of run-off. Let us consider the initial rate of run-off at 8:54 P.M. The values of Q_w and Q_p are 0.101 c.f.s. and 3.30 c.f.s., respectively. With an error of 20%, Q_p would be either 2.64 c.f.s. or 3.96 c.f.s. Using the smaller value $Q = Q_w + Q_p$ would be 0.101 + 2.64 = 2.74 c.f.s. However, if the pondage correction is neglected altogether the value of Q would be 0.101 c.f.s. which is a small fraction of either 3.40 c.f.s. or 2.74 c.f.s. Applying the same reasoning to the rate at 9:10 P.M. an error of 20% in Q_p would, in that case, result in an error of 14% in the actual rate of run-off. Neglecting Q_p would result in an error of 273% or 317%. The above discussion indicates that although the error in Q_p may be considerable it can by no means be neglected if rates of run-off are to be determined with any degree of accuracy. It also shows rather conclusively that when measurements of run-off from very small comparable areas are made for the purpose of determining the effect of a single factor on run-off, care must be exercised to reduce the pondage to an absolute minimum and to eliminate as many as possible of the errors involved in the determination of the pondage correction.

With measuring devices now available the pondage correction cannot be altogether eliminated. Although it may not always be practical to do so, it is theoretically possible to shape the channel of approach at a weir or flume in such a manner as to make the pondage correction for an assumed maximum rate of change in stage negligible

in relation to the rated discharge of the measuring device. With the equation given below one can determine the surface area of the pond which should not be exceeded at a given stage if the pondage correction is to be less than a given percentage of the rate of discharge of the run-off measuring device for an assumed maximum rate of change in stage:

$$A = 0.6 \frac{p}{m} Q_w \text{ . . . . (I)}$$

In this equation:

A is the surface area of the pond in sq. ft. at any stage H.

Q_w is the rated discharge of the flume or weir in c.f.s. at the same stage.

m is the rate of change in stage in feet per minute just before stage H is reached.

p in percent equals $\frac{Q_p}{Q_w} \times 100$, in other words, it indicates what percentage of the rated discharge the pondage correction represents.

By way of illustration, let us determine the maximum allowable area of the pond at stage 1.90' at the station illustrated in figs. 3 and 4, which would permit neglecting the pondage correction for rates of change in stage not exceeding 0.03' per minute if the error involved in neglecting pondage correction is not to exceed 5%. This gives values of m = 0.03, p = 5. From the rating table (fig. 7) Q_w at stage 1.90' is 1.20. Substituting these values in the above equation and solving for A we find:

$$A = 0.6 \times \frac{5}{0.03} \times 1.20 = 120 \text{ sq. ft.}$$

A practical installation for small areas which will tend to make the pondage correction small for the smaller rates of change in stage and will keep it constant throughout the entire range in stage for any given rate of change can be attained by placing the measuring device (flume or weir) below the elevation of the natural channel and confining the pondage to a rectangular box. Such a box must be as small as possible without adversely affecting the performance of the measuring weir or flume. If the box is impervious it will also eliminate the error due to seepage which may be important where small differences in run-off from two comparable areas are studied in establishing trends in the effects of various factors on run-off.

There are a number of implications of the pondage correction which should be of interest both to engineers and hydrologists.

Equation (I) can be written thus,

$$p = 72600 \frac{A}{Q_w} m \text{ . . . . (II).}$$

This converts the units of area from square feet to acres. In this form the equation can be conveniently used to estimate the rates of run-off represented by pondage at any head on a spillway of a small impounding reservoir, if values of "m" are known or can be safely estimated. In this case Q_w is of course the discharge of the spillway at a given head and A the area of the reservoir in acres at the same head.

This equation can also be used in converting the discharge of spillways on small impounding reservoirs into actual rates of surface run-off if the rates of change in stage "m" and the head on the spillways are determined by means of a waterstage recorder properly installed in the reservoir. There are, however, several practical difficulties which may limit the application of this method. Due to the large surface areas which may be involved, a greater degree of refinement in measuring the stage and the rate of change in stage may be required. The determination and application of the pondage correction is further complicated by waves and the back-water curve. Nevertheless, this may be the only method of obtaining rates of run-off from areas which are too small for current meter measurements yet too large for weirs and flumes with a minimum of pondage.

The secondary peaks and other variations brought out in the corrected hydrographs should prove valuable in detailed studies of the rainfall run-off relationship. The student of run-off phenomena may find the pondage correction helpful in verifying correct hypotheses and in overthrowing incorrect ones.

In view of the large errors involved in neglecting the pondage correction and of the errors involved in its determination, especially for run-off stations with natural channels of approach, the tolerances to be adhered to in the construction of precalibrated rate measuring devices need not be very narrow. One must, however, be very careful to keep within tolerances justified by the pondage correction.

The method of determining the time of ending of surface run-off discussed in this paper may prove helpful in segregating surface run-off from ground water flow in cases where channel storage is negligible.

The various uses of the pondage correction mentioned above are merely suggested for consideration. The development of actual methods would require considerable study.

CONCLUSIONS:

1. Pondage corrections must be applied in all cases where rates of surface run-off from small drainage basins are determined by means of measuring devices which create pondage.

2. It is the rate of pondage rather than the volume that determines the magnitude of the pondage correction.

3. The errors involved in neglecting the pondage correction are, as a rule, immesurably greater than those involved in the determination of the pondage correction.

4. In cases where it is necessary to determine rates of run-off from two or more comparable very small watersheds (less than 5 acres) for the purpose of determining the effect of a single factor on run-off every effort must be made to reduce the area of pondage to the absolute minimum consistent with proper operation of the measuring device. If this is done the pondage correction may be negligible for small rates of change in stage. The correction must even then be considered for larger rates of change.

5. The pondage corrections afford a means of determining the actual time of ending of surface run-off and bring out secondary peaks and variations not shown by the uncorrected hydrograph.

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